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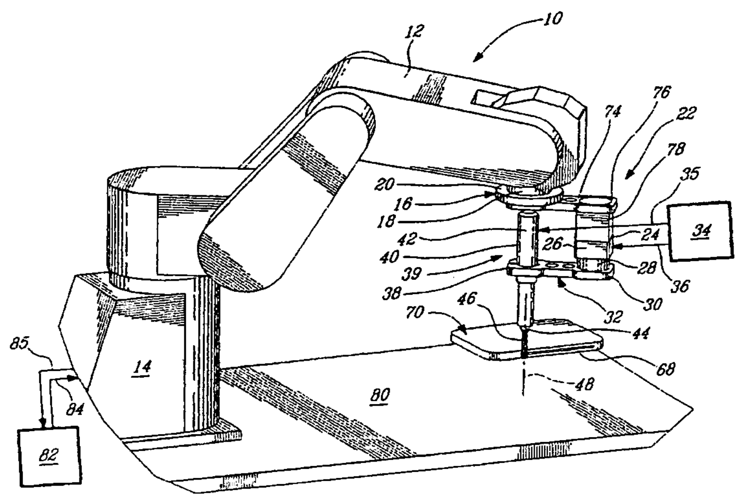
(54) Title: TOOL COMPLIANCE DEVICE AND METHOD



(57) Abstract: A tool compliance device for use with a robot (10) for removing material on a workpiece (70) comprises a tool compliance unit (22) including a rotary actuator (24) having its fixed portion (26) rigidly coupled to a rotary end element (20) integrated at the robot working end and a pivoting end element (28) secured to a pivoting member (32) having a trailing portion supporting a tool assembly (39). The latter is provided with a tool (46) having guides (54, 56) contacting the workpiece (70). In use, the pivoting member (32) is pulled according to a tool working path while the rotary end element (20) brings the fixed portion (26) of the rotary actuator (24) in a position wherein the pivoting member (32) is allowed to pivot with the tool assembly (39) enabling the tool (46) to move within a tool compliance range at a working position along the tool working path upon contact of the guides (54, 56) against the workpiece (70) under torque applied by the rotary actuator (24).

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TOOL COMPLIANCE DEVICE AND METHOD

Field of the invention

The present invention relates generally to compliance devices and methods, and more particularly to compliance devices and method for use with robotic systems for removing material at the surface of workpieces, which compliance devices and methods are employed to adjust the position of the working tool with reference to the workpiece surface.

Brief description of the background art

Robotic systems for performing various tasks such as deburring, milling grinding, chamfering or polishing wherein the material at the surface of the workpiece has to be removed, are known to be provided with compliance devices for correcting the working position of the tool in contact with the surface of the workpiece as compared to programmed position control data as generated by the robot controller, which data may be determined through known tool path teaching or adaptive sensing techniques using vision system or other known sensing devices.

A basic compliance principle consists of effecting adjustment of the position of the tool according to only one axis. An industrial robot device embodying such a linear compliance approach is disclosed in US Patent No 4,637,775 issued on January 20, 1987 to Kato, which is equipped at a working end of the robot arm with a work tool such as a cutting or grinding tool coupled to a friction damper in the form of a spring for suppressing sudden movement of the work tool in the direction of the normal displacement thereof toward and away of the workpiece. Another robotic device using a similar linear compliance approach is disclosed in US Patent No 4,860,500 issued on August 29, 1989 to Thompson, which robotic device uses a low friction movable bearing slide having a moving portion to which is secured a deburring tool and a fixed portion secured to the robot arm, the moving portion being in turn coupled to a pneumatic driver consisting of an air cylinder with a low friction piston. An accumulator is used between an air supply line and the air cylinder such that air pressure against the piston is kept constant. The linear movement of the moving portion with respect to the fixed portion of the bearing slide serves to compensate inaccuracies in a metal removal process which might otherwise be caused by robot path errors. Another example of a robot system using linear compliance approach is disclosed in US Patent No 4,993,896 issued on February 19, 1991 to Dombrowski et al., which discloses an edge contouring system for removing burrs from edges of precision parts, in which the deburring tool is mounted on a compliance device applying a constant force on the tool to keep it in contact with the

part edge, yet permitting movement of the tool in the direction normal to the part surface to accommodate for irregularities in the part geometry. There is also provided a pilot integral with the deburring tool to limit penetration thereof into the depart edge. While the above-mentioned robotic systems are provided with linear compliance devices applying radial or transverse compliance movement for the tool, axial compliance devices are also known such as disclosed in US Patent 5,312,212 issued on May 17, 1994 to Naumec, in which the tool is allowed by the compliance arrangement to be displaced in a direction substantially normal to the surface of the workpiece.

Although of a simple design, the basic linear compliance devices as referred to above all require accurate positioning of the tool by the robot arm according to the program tool path in such a manner that the linear compliance axis is still oriented in a direction parallel to the normal of the workpiece surface. Therefore, robot arm movement programming and controlling are particularly critical to obtain uniform material removing at the surface of the workpiece according to set quality requirements.

In an attempt to improve compliance, multi-axis compliance approaches have been proposed, such as the two-axis compliance device disclosed in US Patent 4,718,798 issued on January 12, 1988 to Dumargue et al., which device uses a plurality of elastic blades disposed around a motor driving a rotary tool mounted on a tool support for a robot. The tool support comprises a first part rigidly connected to the robot and a second part supporting the motor, wherein the elastic blades are connected at opposed ends thereof to the first and second parts through a swivel joint assembly and an articulation respectively, to provide two-access radial compliance. Although representing an improvement over single axis linear compliance, the compliance device as taught by Dumargue is of a complex design, and may require maintenance due to possible wear of elastic plates. A variant of the two-access radial or transverse compliance approach is applied to an apparatus for removing flash from a flash-forming region of a polymeric molded product as disclosed in US Patent 4,979,283 issued on December 25, 1990 to Kurita et Al., which apparatus uses a reamer controlled in radial position according to the shape of the polymeric molded product so that it always receives a constant radial load from the product to lead even traces after flash removal. Such result is obtained with the use of a plurality of springs uniformly distributed around the body of the tool driving unit and attached thereto through respective first hooks, which springs are provided with second hooks secured to a driving tool holder attached to a free-working end of the robot arm. In such arrangement, radially opposed springs cooperate in tension and compression respectively, to provide two-axis radial compliance for the rotary tool. Although offering improved compliance flexibility as compared to the axial single axis

compliance approach, such two-axis compliance device is of a rather complex design involving numerous moving parts that may require regular maintenance to ensure proper working. A different two-axis compliance approach as been proposed in US Patent 4,884,941 issued on December 5, 1989 to Kazerooni, which discloses an end-effector for use with a robotic manipulator comprising a planar linkage having input links driven by motors which are coupled to an output link on which a driving unit for a rotary tool is mounted. A force sensor is connected to the output link and the tool mount for measuring two interaction forces to generate corresponding signals. Sensors are also provided at the input links to measure angular displacement and velocity thereof, all signals being used by a controller for controlling the drive motors to provide active electronic compliance. With such integrated control end-effector, a sophisticated controlling program must be employed to generate control signals to motors in order to achieve desired stiffness compliance in the normal and tangential directions at the working position of the tool along the working path, from the normal and tangential force signals as well as the angular displacement and velocity signals generated by the various sensors used.

Another compliance approach that is simpler to implement compared to the two-axis approach is described in US Patent 4,753,048 issued on June 28, 1998 to Asada et al., in which a pivoting axis about which a rotary grinding tool is caused to pivot so as to provide required compliance between the rotary tool and the surface of the workpiece to be treated. More specifically, the proposed method involves adding compliance to the grinding tool in the tangential direction while maintaining higher stiffness in the normal direction. Such method is limited to workpieces that do not present high-variability in the normal direction of the surface due to low-compliance maintained in the normal direction. A similar two-axis, pivoting compliance approach applied to an automatic polishing machine is disclosed in US Patent 4,907,371 issued on March 13, 1990 to Shoda et al. The use of such apparatus is limited to polishing of elongated workpieces involving near-linear tool working paths. Another pivoting compliance device is disclosed in US Patent 5,157,823 issued on October 27, 1992 to Delaval et al., which device is used for supporting a milling tool attached to a robot arm by providing first and second support members attached to one another by torsion bar elements so that the second member on which is mounted the machining tool is movable with respect to the first member about an axis in a single degree of freedom. Since the pivot axis always remains parallel to the tangent of the trajectory described by the milling tool end, the pivoting movement of the second support member induces a corresponding variation of the tool attack therefor resulting in milling non-uniformities. A

similar approach is also used in the industrial robot compliant end-effector as disclosed in US Patent 5,765,975 issued on June 16, 1998 to Hoffmann et Al. Although a guide is provided for limiting the movement of the tool by engaging the workpiece near the area to be cut and trimmed, variations in the tool attack angle may affect the quality of the end result.

Therefore, there is still a need for a simple and compact tool compliance device for use with automated systems adapted to perform material moving tasks such as deburring, milling, grinding or the like on workpiece of various shapes.

Summary of the invention

It is therefore a main object of the present invention to provide a simple and compact tool compliance device and method for use with a system for removing material at the surface of workpiece of various shapes, which are capable of adapting to dimensional variations of the surface of a workpiece to be processed along a tool working path associated therewith.

According to the above object, from a broad aspect, there is provided a tool compliance device for use with a system for removing material at the surface of a workpiece including a robot having a working end provided with axial rotary drive means having a rotary end element, a controller for moving said working end according to a tool working path, a tool assembly provided with a tool extending along a tool working axis and tool guide means contacting a workpiece-related reference surface. The device comprises a tool compliance unit including pivoting drive means having a fixed portion rigidly coupled to the rotary end element and a pivoting end element secured to a leading portion of a pivoting member having a trailing portion receiving said tool assembly. The pivoting member is pulled according to the tool working path while the rotary end element brings the fixed portion of the pivoting drive means in a position wherein the pivoting member is allowed to pivot with the tool assembly enabling the tool to move within a tool compliance range at a working position along the tool working path upon contact of the guide means against the workpiece-related reference surface under torque applied by the pivoting drive means, so that the tool compliance range has a non-null component parallel to a normal axis extending from the workpiece surface through the working position to provide compliance of the tool with the workpiece while removing material therefrom.

According to another broad aspect of the present invention, there is provided an apparatus for removing material at the surface of a workpiece for use with a robot having a working end provided with axial rotary drive means having a rotary end element, and a controller for moving said working end according to a tool working path.

The apparatus comprises a tool compliance unit including pivoting drive means having a fixed portion rigidly coupled to the rotary end element and a pivoting end element secured to a leading portion of a pivoting member, and a tool assembly mounted on a trailing portion of the pivoting member and provided with a tool extending along a tool working axis, and tool guide means contacting a workpiece-related reference surface. The pivoting member is pulled according to the tool working path while the rotary end element brings the fixed portion of the pivoting drive means in a position wherein the pivoting member is allowed to pivot with a toll assembly for enabling the tool to move within a tool compliance range at a working position along the tool working path upon contact of the guide means against the workpiece-related reference surface under torque applied by the pivoting drive means, so that the tool compliance range has a non-null component parallel to a normal axis extending from the workpiece surface through the working position to provide compliance of the tool with the workpiece while removing material therefrom.

According to a further broad aspect of the invention, there is provided a system for removing material at the surface of a workpiece comprising a robot having a working end provided with axial rotary drive means having a rotary end element, and a controller for moving said working end according to a tool working path. The system further comprises a tool compliance unit including pivoting drive means having a fixed portion rigidly coupled to the rotary end element and a pivoting end element secured to a leading portion of a pivoting member, and a tool assembly mounted on a trailing portion of the pivoting member and provided with a tool extending along a tool working axis, and tool guide means contacting a workpiece-related reference surface. The pivoting member is pulled according to the tool working path while the rotary end element brings the fixed portion of the pivoting drive means in a position wherein the pivoting member is allowed to pivot with the tool assembly enabling the tool to move within a tool compliance range at a working position along the tool working path upon contact of the guide means against the workpiece-related reference surface under torque applied by the pivoting drive means, so that said tool compliance range has a non-null component parallel to a normal axis extending from the workpiece surface through the working position to provide compliance of the tool with the workpiece while removing material therefrom.

According to a still further broad aspect of the present invention, there is provided a method of controlling a tool for removing material at the surface of a workpiece while providing compliance of said tool with said surface. The method includes the steps of: a) supporting the tool on a trailing portion of a pivoting member having a leading portion defining a pivot axis; b) applying a torque on the pivoting

member while guiding the tool onto a workpiece-related reference surface; and c) creating relative motion between the pivot axis and said surface according to a tool working path so that the pivoting member is allowed to pivot about the pivot axis for enabling the tool to move within a tool compliance range at a working position along the tool working upon the application of said torque, so that the tool compliance range has a non-null component parallel to a normal axis extending from the workpiece surface through the working position to provide compliance of the tool with the workpiece while removing material therefrom.

Brief description of the drawings

A preferred embodiment of the tool compliance device and method as well as apparatus and system for removing material at the surface of a workpiece will now be explained in detail with reference to the accompanying drawings in which:

Fig.1 is a perspective view of the robot system for removing material at the surface of a workpiece according to the invention, which shows a robot arm to which is mounted a tool compliance unit supporting a tool assembly in accordance with a preferred embodiment of the present invention used for deburring a molded plastic article;

Fig.2 is a partial side elevation view of the system of Fig.1, showing the tool compliance unit and tool assembly in more detail;

Fig.3 is a side elevation view of a deburring tool as provided in the embodiment of Fig.1;

Fig.4 is a cross-sectional end view of the deburring tool of Fig.3 according to section line 4-4, showing in section the cutting element defining a cutting edge;

Fig.5 is a cross-sectional top plan view of the tool compliance unit according to section lines 5-5 of Fig.2, showing the tool compliance unit with the tool assembly in a first working position along a tool working path corresponding to a periphery of a workpiece provided with a burr to be removed;

Fig.6 is a cross-sectional top plan view similar to Fig.5, showing the tool compliance unit with the tool assembly in a second working position along the tool working path upstream from the position shown in Fig.5;

Fig.7 is a cross-sectional top plan view of the tool compliance unit similar to Fig.6, showing a workpiece presenting dimensional variation of one side thereof as compared to working tool path data generated by the robot controller;

Fig.8 is an end elevation view similar to Fig.2, showing the robot system in a position to remove a burr remaining on the side surface of a workpiece, which burr

presents an angle at a portion thereof with reference to a horizontal plane, the tool working path presenting a three-dimensional configuration.

Detailed description of the preferred embodiment

Referring now to Fig. 1, a first preferred embodiment of a system for removing material at the surface of a workpiece will now be described in the context of a deburring application involving molded plastic parts. However, it is to be understood that the present invention can be used for other purposes such as milling, grinding, chamfering or polishing workpiece made of various material such as metal or wood, provided appropriate tools are employed. The robot system generally designated at numeral 10 comprises a robot arm 12 mounted on a base 14. In the example shown in Fig.1 a multi-access robot system model No. LR-MATED 200I manufactured by Fanuc is illustrated. However, it is to be understood that any suitable multi-access robot system using robot arm or gantry device available in the market place may be used for the purpose of the present invention. A robot working end 16 is provided with axial rotary drive means in the form of an integrated rotary actuator 18 having a rotary end element in the form of a mounting disk 20. The robot system 10 further comprises a tool compliance unit generally designated at 22 including pivoting drive means in the form of a pneumatic rotary actuator 24 having a fixed portion 26 rigidly coupled to the mounting disk 20 and a pivoting end element 28 secured to a leading portion 30 of a pivoting member 32. For controlling the pneumatic rotary actuator 24, there is provided a controlled pressure air source 34 having an output supply line 36 linked to a corresponding input on the rotary actuator 24. Although pneumatic rotary actuator 24 and air source 34 are preferably used to control the working torque at a level that is appropriate to plastic article deburring, other types of actuating devices may be used for this or other applications, such as hydraulic or electric actuators. Mounted on a trailing portion 38 of pivoting member 32 is a tool assembly 39 including a rotary tool driving device 40 including a controlled RPM rotary actuator 42 provided with a tool holder or chuck 44 adapted to receive a deburring tool 46 which is secured thereto for rotation about a tool working axis 48 upon operation of the rotary actuator 42. The rotary actuator 42 is fed through line 35 with air under pressure as generated by pressured air source 34, or by any other suitable independent air supply source. It is to be understood that depending upon the application involved, other types of rotary actuators may be contemplated, according to the specific application requirements in terms of tool RPM, torque, etc. Moreover, some applications may not require the use of a rotating tool such as trimming operations implying stationary blades or scrapers. Turning now to Fig.3, the deburring tool 46 has a body or shank 50 adapted to engage the chuck 44 mentioned

above, and a trimming head 52 having a proximal cylindrical guide portion 54 adjacent to the shank 50 and a distal cylindrical guide portion 56. Cylindrical guide portions 54, 56 serve as tool guide means as will be later explained in more detail. Alternatively, annular bearings may also be used as guiding elements. The tool 46 further has at least one cutting element 58 made of hard material and having a cutting edge 60 adjacent to cylindrical guide portions 54, 56 so that cutting edge 60 extends between proximal and distal cylindrical portions 54, 56.

Turning now to Fig.4, it can be seen that the cutting element 58 preferably defines first and second surfaces 62, 64 which intersect according to a predetermined angle to form the cutting edge 60. It can also be seen from Fig.4 that first surface 62 is preferably coplanar with tool working axis 48 represented as entering through the figure and that the rotary actuator 42 is caused to rotate about tool working axis 48 in a direction represented by arrow 66 so that coplanar surface 62 of the cutting element 58 removes burr material 68 present on the surface of the workpiece 70 toward a direction of motion of the tool along the tool working path as indicated by arrow 72. It is to be understood that a tool showing a different design adapted to work according to a counter-clockwise direction as opposed to the clockwise direction shown by arrow 66 of Fig.3 may also be used depending on the application considered. Moreover, the trimming head 52 of the tool 46 could be provided with a plurality of cutting elements 58 distributed along the perimeter of the trimming head 52. In the example shown in Fig.3, the trimming head is especially designed for deburring workpieces made of plastic material such as polyethylene parts produced by known blow or injection plastic molding processes, in that the cutting edge 60 is characterized by an arcuate profile a portion of which extending beyond the outer diameter of proximal and distal cylindrical guide portions 54, 56 to remove burr material in a particularly efficient way. Although the proximal and distal cylindrical guide portions 54, 56 are of the same outer diameter in the example shown in Fig.3, it is to be understood that a different configuration for the cutting element 58 may be employed that could either involve cylindrical guide portions of different diameters adapted to the shape of the workpiece to be processed, or involve a single guide portion as part of the trimming head 52. Furthermore, for other applications such as thin board edge trimming, a separate guiding device which is not part of the tool itself may be attached to another portion of the tool assembly and adapted to cooperate with another workpiece-related reference surface such as the edge of a template designed for a specific article, to provide the same guiding function as obtained with cylindrical guide portions 54, 56 upon contact thereof against the workpiece surface areas on both sides of burr 68 acting as workpiece-related reference surface. It can also

be seen from Fig.3 that the outer diameter of cylindrical guide portions 54, 56 is larger than the outer radial dimension of the tool shank 50 for providing clearance thereof on both sides of burr 68.

It can be seen from Fig.1 that the robot base 14 is installed on a platform 80 on which the workpiece 70 to be processed is rigidly mounted with some attachment means (not shown). The robot system is also provided with a robot controller 82 that generated control data sent to the robot through a communication line 84 and receives robot sensor input data through communication line 86. For the Fanuc LR-MATES 200I robot as illustrated in Fig.1, a Fanuc RJ-3 type controller may be programmed according to a tool working path dictated by the periphery of the workpiece 70 to be deburred. The programmed tool working path may be generated with a known point teaching method such as implemented by a teach pendant program (TPP) software module such as the Fanuc Tarel^MC software module. In order to optimize speed control of the robot-working end 16 according to the program tool working path, Fanuc Accupath^MC control software module is preferably implemented in the controller 82.

Preferably, the tool assembly 39 is mounted on the trailing portion 38 of the pivoting member 32 so that the tool working axis 48 extends substantially through a tool centre point (TCP) of the robot working end, so as to minimize displacement speed of the robot working end 16 that is required to induce responding travelling speed of the tool assembly along the tool working path. The tool compliance unit 22 is preferably provided with a holding member 74 for rigidly coupling the fixed portion 26 of the rotary actuator 24 to the rotary actuator 18 integrated into the robot arm 12, the holding member 74 having a leading portion 76 rigidly secured to fixed portion 26 of the rotary actuator 24 by means of a spacing member 78 disposed between leading portion 76 of the holding member 74 and fixed portion 26 of the rotary actuator 24, for securing thereof one another. The trailing portion 77 of holding member 74 is rigidly secured to the mounting disk 20. Although the fixed portion 26 could be secured directly under the leading portion 76 of holding member 74, the spacing member 78 is preferably used to provide higher clearance between holding member 74 and pivoting member 32 for the rotary tool driving device 40, so as to minimize levering effect due to the length of the rotary actuator 42 extending beyond pivoting member 32 toward trimming head 52, which otherwise may cause vibration problems.

The method of operation of the robot system and compliance device according to the present invention will be now explained with reference to Figs.2-8. Referring to Fig.2 in view of Fig.5, it can be seen that the pivoting member 32 is allowed to pivot about a pivot axis 86 which preferably extends substantially perpendicular to a tangent of

the tool working path at a working position as indicated by tangent line 88, which pivot axis 86 is represented as entering through the view of Fig.5. Such relationship between the pivot axis 86 and the tangent 88 of the tool working path at working position 90 is preferably maintained to prevent variation of attack angle of the trimming head 52 of the tool 46 with respect to the workpiece bearing surface, to ensure uniform deburring. It is to be understood that for some applications, such perpendicular relationship may not be required. For the tool position shown in Fig.5, which position is intermediate between a tool path starting point 92 and an adjacent tool path end point 94 corresponding to the end of burr 68, the tool trimming head 52 is located at working position 90 on a roundness of workpiece 70. It can be appreciated that at such location, reference axis 96 defined by the leading portion 76 of the holding member 74 and the integrated rotary actuator 18, may not be parallel to the tangent 88 passing at working position 90. However, turning to Fig.6 which shows compliance unit 22 in a position wherein the trimming end 52 is advanced further toward the end of burr 68, reference axis 96 is brought substantially parallel to the tangent 88 of the tool working path at working position 90'. Such parallel relationship between reference axis 96 and workpiece surface tangent 88 at working position 90' provides maximum compliance of the trimming head 52 with the workpiece surface in a direction parallel to a normal axis 98 extending from the workpiece surface through the working position 90', as will be explained later in more detail.

In operation, a user of the robot system first rigidly attaches the workpiece 70 to the platform 80, and then performs robot programming through the controller 82, by proceeding with a point teaching operation along the periphery of the workpiece defined by the surface to be processed. Alternatively, the robot system may be provided with some adaptive control means for generating off-line or in-line tool working path data. For example, a vision system using one or more cameras may be coupled through an image-processing device to the controller for feeding thereto tool working path data. As a first step of the deburring operation of workpiece 70, the controller 82 sends through communication line 84 command signals to the robot arm 12 for causing the trimming head 52 to be displaced to the tool path start point 92 shown in fig.5, so that proximal and distal cylindrical guide portions 54,56 of the trimming head 52 are in contact with the workpiece surface on both sides of the burr 68, while the leading portion 76 of the holding member 74 is brought to a position ahead of trimming head 52. Then, following activation of the controller by the user, the leading portion 30 of the pivoting member 32 is pulled under traction of the holding member 74 according to the tool working path indicated by arrows 100 while the rotary end element 18 shown in Fig.2 brings the fixed

portion 26 of the pneumatic rotary actuator 24 in a position wherein the pivoting member 32 is allowed to pivot with the tool assembly 39 about the pivot axis 86 for enabling the tool 46 to move within a tool compliance range at the working position along the tool working path as indicated by numerals 90, 90' upon contact of the cylindrical guide portions 54, 56 of the trimming head 52 against the workpiece edge considered as a workpiece-related reference surface, under the torque applied by the rotary actuator 42. It can be appreciated that with the tool compliance unit 22 according to the invention, the tool compliance range represented as vector "C" has a non-null component "C_n" parallel to the normal axis 98, 98' extending from the workpiece surface through the working position 90, 90' respectively, to provide compliance of the tool 46 with the workpiece 70, while removing material therefrom. Referring now to Fig.7, there is shown a workpiece 70' that presents a dimensional variation of a side wall 102 thereof, which variation presented by the symbol "v" has been exaggerated for the purpose of explanation. It can be seen that the holding member 74 is brought in a position so that reference axis 96 is maintained substantially parallel to tangent 88 of the tool working path corresponding to working position 90" even if the considered portion of the tool working path does not correspond to the surface of side wall 102. Furthermore, the pivoting member 32 is still allowed to pivot about pivot axis 86 so as to enable the trimming head 52 of the tool to move within to the compliance range "C" at working position 90" wherein tool compliance range "C" still has a component "C_n" that is parallel to normal axis 98 extending from the workpiece surface through working position 90". It can be appreciated that for the tool positions shown in Fig.5 and 7 there is a non-null compliance component "C_t" that is tangent to the workpiece surface at working position 90, 90" respectively, whereas such tangential component "C_t" has a null value with "C_n" equals "C" at the tool position shown in Fig.6. While it is preferable to have "C_n" = "C" along the most part of the working path to maximize compliance efficiency, experience has shown that sufficient compliance is obtained insofar the normal compliance components "C_n" is maintained above a predetermined minimal level by controlling the movement of the rotary actuator 18 accordingly. Typically, for a deburring application using the device according to the preferred embodiment described above on workpieces made of polyethylene, the deburring tool may be driven at about 20,000 RPM with a tool traveling speed typically from about 50 mm/s for complex edge surface to about 200 mm/s for regular edge surface. The compliance range may be of about +/- 1.0 inch, with air pressure fed to the pneumatic rotary actuator set to about 60 psi, with a typical tool penetration from near 0 to about 0.01 inch for a typical burr width from 1/16 to about 1/8 inch. It can be appreciated in view of Fig.5 that with the principle of positioning the pivoting member 32

so that the tool working axis 48 extends substantially through the tool centre point (TCP) of the robot working end 16, the displacement speed of the latter is maintained substantially at the same value as the tangential speed of the tool 46 along the workpiece surface to ensure uniform material removing. This feature is particularly advantageous compared to known linear one-axis compliance device for which the robot working end has to be moved at a speed higher than the tangential speed of the tool at roundness portions of the workpiece. Whenever the speed of the robot working end approaches its nominal maximum value, speed control at such maximum value is more difficult to achieve and consequently, uniformity of material removing cannot be guaranteed. Furthermore, the compliance device and method according to the invention has proved to provide good trimming head behavior even at abrupt working path variations while minimizing the number of points to be taught by the robot. Moreover, high tool travelling speed can be handled while providing high quality surface finish.

Turning now to Fig. 8, the robot system 10 is shown in a position to remove a burr 68' remaining on the side wall 102' of a workpiece 70", which burr 68' presents an angle at a portion 103 thereof with reference to a reference horizontal plane represented by axis 104. In order to move the tool assembly 39 in a forward deburring direction along the angularly extending portion 103 of burr 68" as indicated by arrow 106, the robot arm 12 is controlled to move its working end 16 in a corresponding angular orientation as shown in Fig. 8 as the trimming head is displaced along working path portion 103. Therefore, the compliance device according to the present invention can be used to remove material at the surface of workpieces presenting various shapes, involving both planar and three-dimensional working path configurations. It is to be understood that the compliance device and method according to the present invention may also be advantageously used in applications where the workpiece is being displaced by suitable automated means with respect to a stationary tool assembly provided with the compliance device according to the invention.

We claim :

1. A tool compliance device for use with a system (10) for removing material at the surface of a workpiece (70) including a robot having a working end (16) provided with axial rotary drive means (18) having a rotary end element (20), a controller (82) for moving said working end (16) according to a tool working path, a tool assembly (39) provided with a tool (46) extending along a tool working axis (48) and tool guide means (54,56) contacting a workpiece-related reference surface, said device being characterized by comprising:

a tool compliance unit (22) including pivoting drive means (24) having a fixed portion (26) rigidly coupled to said rotary end element (20) and a pivoting end element (28) secured to a leading portion (30) of a pivoting member (32) having a trailing portion (38) receiving said tool assembly (39);

wherein said pivoting member (32) is pulled according to said tool working path while the rotary end element (20) brings the fixed portion (26) of the pivoting drive means (24) in a position wherein the pivoting member (32) is allowed to pivot with the tool assembly (39) enabling the tool (46) to move within a tool compliance range at a working position along the tool working path upon contact of the guide means (54,56) against the workpiece-related reference surface under torque applied by the pivoting drive means (24), so that said tool compliance range has a non-null component parallel to a normal axis (98) extending from the workpiece surface through the working position to provide compliance of the tool (46) with the workpiece while removing material therefrom.

2. The device according to claim 1, wherein said pivoting member (32) is allowed to pivot about a pivot axis (86) extending substantially perpendicular to a tangent (88) of said tool working path according to said working position.

3. The device according to claim 1, wherein said tool compliance unit (22) further includes a holding member (74) for rigidly coupling the fixed portion (26) of said pivoting drive means (24) to said rotary element (20), said holding member (74) having a leading portion (76) rigidly secured to the fixed portion (26) of the pivoting drive means (24), and a trailing portion (77) rigidly secured to the rotary end element (20).

4. The device according to claim 3, wherein said holding member (74) is brought in a position so the working axis (48) is maintained substantially perpendicular to said normal axis (98) and to a tangent (88) of said tool working path.

5. The device according to claim 3, wherein said tool compliance unit (22) further includes a spacing member (78) disposed between the leading portion (76) of said holding member (74) and the fixed portion (26) of said pivoting drive means (24) for securing thereof with one another.

6. The device according to claim 3, wherein said pivoting member (32) is allowed to pivot about a pivot axis (86) extending substantially perpendicular to a tangent (88) of said tool working path according to said working position, the leading portion (76) of said holding member (74) and said rotary end element (20) defining a reference axis (96) passing therethrough, said holding member being brought in a position so that said reference axis (96) is maintained substantially parallel to the tangent (88) of said tool working path.

7. The device according to claim 6, wherein said holding member (74) is brought in said position so that said working axis (48) is maintained substantially perpendicular to said normal axis (98) and to the tangent of said tool working path.

8. The device according to claim 1 or 7, wherein said tool assembly (39) is mounted on the trailing portion (38) of said pivoting member (32) so that the tool working axis (48) extends substantially through a tool center point of said working end (16).

9. The device according to claim 1, wherein said pivoting drive means (24) comprise a pneumatic actuator connected to a controlled pressure air source (34).

10. An apparatus for removing material at the surface of a workpiece (70) for use with a robot having a working end (16) provided with axial rotary drive means (18) having a rotary end element (20), and a controller (82) for moving said working end (16) according to a tool working path, said apparatus being characterized by comprising:

a tool compliance unit (22) including pivoting drive means (24) having a fixed portion (26) rigidly coupled to said rotary end element (20) and a pivoting end element (28) secured to a leading portion (30) of a pivoting member (32); and

a tool assembly (39) mounted on a trailing portion (38) of the pivoting member (32) and provided with a tool (46) extending along a tool working axis (48), and tool guide means (54,56) contacting a workpiece-related reference surface;

wherein said pivoting member (32) is pulled according to said tool working path while the rotary end (20) element brings the fixed portion (26) of the pivoting drive means (24) in a position wherein the pivoting member (32) is allowed to pivot with the tool

assembly (39) for enabling the tool (46) to move within a tool compliance range at a working position along the tool working path upon contact of the guide means (54,56) against the workpiece-related reference surface under torque applied by the pivoting drive means (24), so that said tool compliance range has a non-null component parallel to a normal axis (98) extending from the workpiece surface through the working position to provide compliance of the tool (46) with the workpiece while removing material therefrom.

11. The apparatus according to claim 10, wherein said pivoting member (32) is allowed to pivot about a pivot axis (86) extending substantially perpendicular to a tangent (88) of said tool working path according to said working position.

12. The apparatus according to claim 10, wherein said tool compliance unit (22) further includes a holding member (74) for rigidly coupling the fixed portion (26) of said pivoting drive means (24) to said rotary element (20), said holding member (74) having a leading portion (76) rigidly secured to the fixed portion (26) of the pivoting drive means (24), and a trailing portion (77) rigidly secured to the rotary end element (20).

13. The apparatus according to claim 12, wherein said holding member (74) is brought in a position so the working axis (48) is maintained substantially perpendicular to said normal axis (98) and to a tangent (88) of said tool working path.

14. The apparatus according to claim 12, wherein said tool compliance unit (22) further includes a spacing member (78) disposed between the leading portion (76) of said holding member (74) and the fixed portion (26) of said rotary drive means (24) for securing thereof with one another.

15. The apparatus according to claim 12, wherein said pivoting member (32) is allowed to pivot about a pivot axis (86) extending substantially perpendicular to a tangent (88) of said tool working path according to said working position, the leading portion (76) of said holding member (74) and said rotary end element (20) defining a reference axis (96) passing therethrough, said holding member being brought in a position so that said reference axis (96) is maintained substantially parallel to the tangent (88) of said tool working path.

16. The apparatus according to claim 15, wherein said holding member (74) is brought in said position so that said working axis (48) is maintained substantially perpendicular to said normal axis (98) and to the tangent of said tool working path.

17. The apparatus according to claim 10 or 16, wherein said tool assembly (39) is mounted on the trailing portion (38) of said pivoting member (32) so that the tool working axis (48) extends substantially through a tool center point of said working end (16).

18. The apparatus according to claim 10, wherein said tool guide means (54,56) are part of said tool (46).

19. The apparatus according to claim 10, wherein said tool assembly (39) comprise rotary tool drive means (40) provided with a tool holder (44) to which said tool (46) is secured for rotation about said working axis (48) upon operation of said tool drive means (40).

20. The apparatus according to claim 19, wherein said apparatus is a deburring apparatus for removing a burr (68) at the surface of a workpiece (70), said tool guide means (54,56) being part of said tool (46), the tool (46) comprising a body (50) secured to said holder (44) and a trimming head (52) including the guide means (54,56) and at least one cutting element (58) having a cutting edge (60) adjacent the guide means (54,56).

21. The apparatus according to claim 20, wherein said guide means (54,56) include a proximal cylindrical guide portion (54) adjacent said body (50) and a distal cylindrical guide portion (56), said cutting edge (60) extending between said proximal and distal portions (54,56).

22. The apparatus according to claim 21, wherein said cylindrical guide portions (54,56) are of a same outer diameter which is larger that the outer radial dimension of said tool body (60) for providing clearance therefor on both sides of said burr (68).

23. The apparatus according to claim 21, wherein said cutting element (58) defines first and second surfaces (62,64) which intersect according to a predetermined angle to form said cutting edge (60).

24. The apparatus according to claim 23, wherein said first surface (62) is coplanar with said tool working axis (48), said rotary tool drive means (40) is rotating about the tool working axis (48) in a direction (66) so that the coplanar first surface (62) of the cutting

element (58) removes material toward a direction of motion (72) of the tool along the tool working path.

25. The apparatus according to claim 23, wherein said workpiece is made of plastic material, said cutting edge (60) is characterized by an arcuate profile a portion of which extending beyond said outer diameter to remove said burr (68).

26. The apparatus according to claim 10, wherein said pivoting means (24) comprise a pneumatic actuator connected to a controlled pressure air source (34).

27. A system (10) for removing material at the surface of a workpiece (70) comprising:

a robot having a working end (16) provided with axial rotary drive means (18) having a rotary end element (20), and a controller (82) for moving said working end (16) according to a tool working path; said system being characterized by further comprising:

a tool compliance unit (22) including pivoting drive means (24) having a fixed portion (26) rigidly coupled to the rotary end element (20) and a pivoting end element (28) secured to a leading portion (30) of a pivoting member (32); and

a tool assembly (39) mounted on a trailing (38) portion of the pivoting member (32) and provided with a tool (46) extending along a tool working axis (48), and tool guide means (54,56) contacting a workpiece-related reference surface;

wherein said pivoting member (32) is pulled according to said tool working path while the rotary end (20) element brings the fixed portion (26) of the pivoting drive means (24) in a position wherein the pivoting member (32) is allowed to pivot with the tool assembly (39) enabling the tool (46) to move within a tool compliance range at a working position along the tool working path upon contact of the guide means (54,56) against the workpiece-related reference surface under torque applied by the pivoting drive means (24), so that said tool compliance range has a non-null component parallel to a normal axis (98) extending from the workpiece surface through the working position to provide compliance of the tool (46) with the workpiece while removing material therefor.

28. The system according to claim 27, wherein said pivoting member (32) is allowed to pivot about a pivot axis (86) extending substantially perpendicular to a tangent (88) of said tool working path according to said working position.

29. The system according to claim 27, wherein said tool compliance unit (22) further includes a holding member (74) for rigidly coupling the fixed portion (26) of said pivoting

drive means (24) to said rotary element (20), said holding member (74) having a leading portion (76) rigidly secured to the fixed portion (26) of the rotary drive means (24), and a trailing portion (77) rigidly secured to the rotary end element (20).

30. The system according to claim 29, wherein said holding member (74) is brought in a position so that said tool working axis (48) is maintained substantially perpendicular to said normal axis (98) and to a tangent of said tool working path.

31. The system according to claim 29, wherein said tool compliance unit (22) further includes a spacing member (78) disposed between the leading portion (76) of said holding member (74) and the fixed portion (26) of said rotary drive means (24) for securing thereof with one another.

32. The system according to claim 29, wherein said pivoting member (32) is allowed to pivot about a pivot axis (86) extending substantially perpendicular to a tangent (88) of said tool working path according to said working position, the leading portion (76) of said holding member (74) and said rotary end element (20) defining a reference axis (96) passing therethrough, said holding member being brought in a position so that said reference axis (96) is maintained substantially parallel to the tangent (88) of said tool working path.

33. The system according to claim 32, wherein said holding member (74) is brought in a position so that said tool working axis (48) is maintained substantially perpendicular to said normal axis (96) and to the tangent (88) of said tool working path.

34. The system according to claim 27 or 33, wherein said tool assembly (39) being mounted on the trailing portion (38) of said pivoting member (32) so that said tool working axis (48) extends substantially through a tool center point of said working end (16).

35. The system according to claim 27, wherein said tool guide means (54,56) are part of said tool (46).

36. The system according to claim 27, wherein said tool assembly (39) comprise rotary tool drive means (40) provided with a tool holder (44) to which said tool (46) is secured for rotation about said tool working axis upon operation of said tool drive means (40).

37. The system according to claim 27, wherein said pivoting drive means (24) comprises a fluid actuator connected to a controlled pressure fluid source (34).

38. The system according to claim 37, wherein said fluid actuator is a pneumatic actuator, said fluid source (34) being a pressurized air source.

39. A method of controlling a tool (46) for removing material at the surface of a workpiece (77) while providing compliance of said tool (46) with said surface, said method being characterized by including the steps of:

a) supporting said tool (46) on a trailing portion (38) of a pivoting member (32) having a leading portion (30) defining a pivot axis (86);

b) applying a torque on said pivoting member (32) while guiding the tool (46) onto a workpiece-related reference surface; and

c) creating relative motion between said pivot axis (86) and said surface according to a tool working path so that the pivoting member (32) is allowed to pivot about the pivot axis (86) for enabling the tool (46) to move within a tool compliance range at a working position along the tool working path upon the application of said torque, so that said tool compliance range has a non-null component parallel to a normal axis (98) extending from the workpiece surface through the working position to provide compliance of the tool (46) with the workpiece while removing material therefrom.

40. The method according to claim 39, wherein said pivot axis (86) extends substantially perpendicular to a tangent (88) of said tool working path according to said working position.

41. The method according to claim 39, wherein said tool (46) extends along a tool working axis (48), said relative motion being created so that the tool working axis (48) is maintained substantially perpendicular to said normal axis (98) and to a tangent (88) of said tool working path.

42. The method according to claim 39, further including simultaneously to said step c) the step of:

d) rotating said tool (46) about said working axis (48).

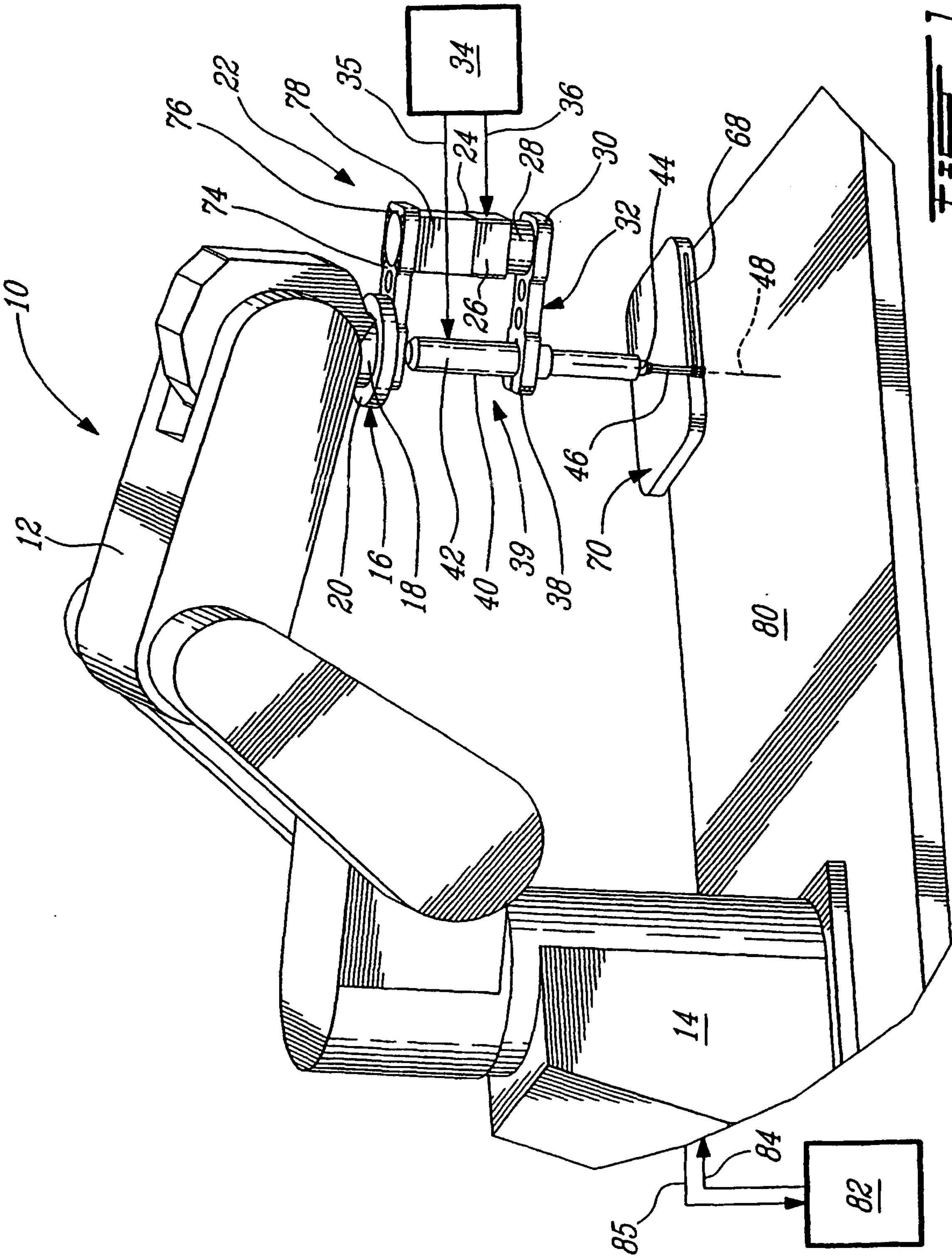
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FIG-1

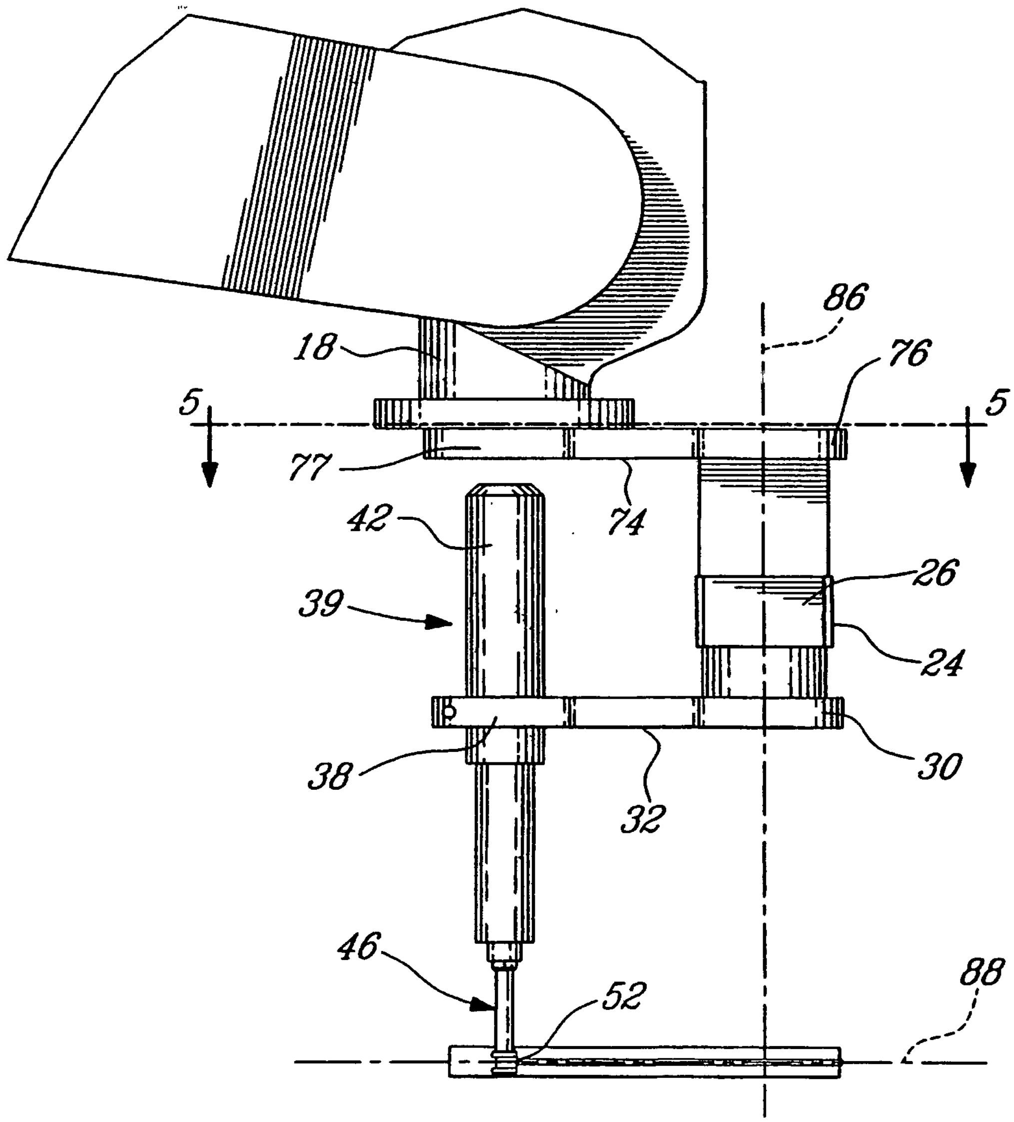


FIG. 2

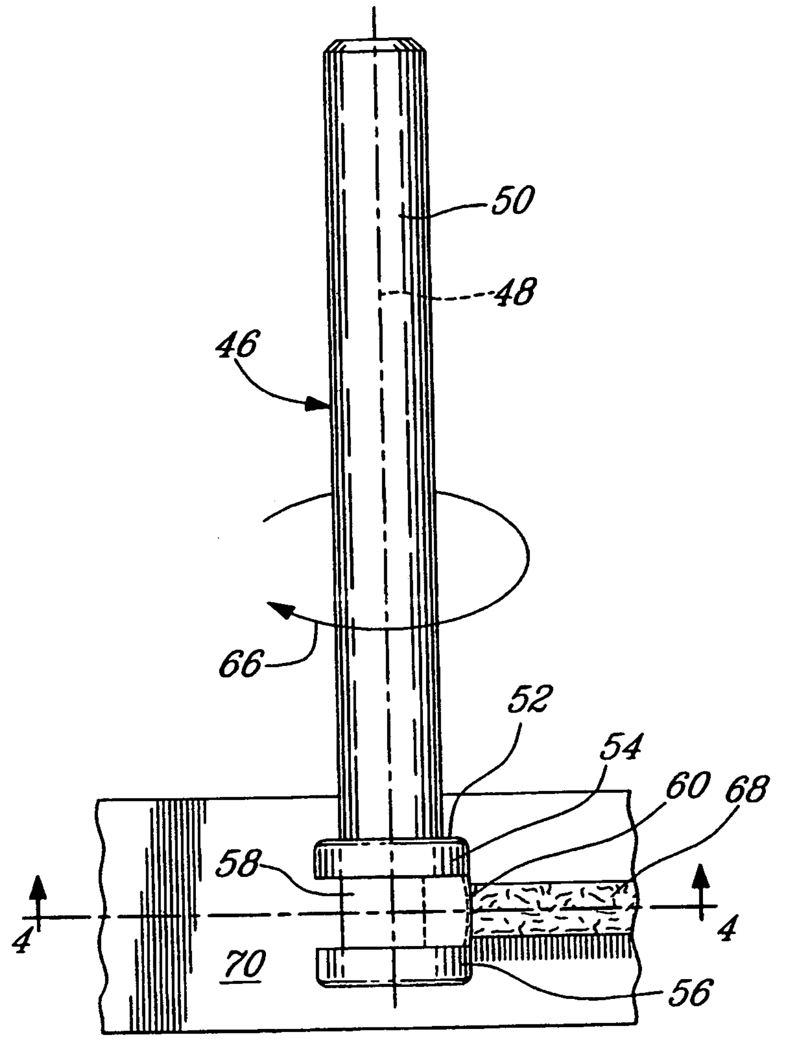


FIG. 3

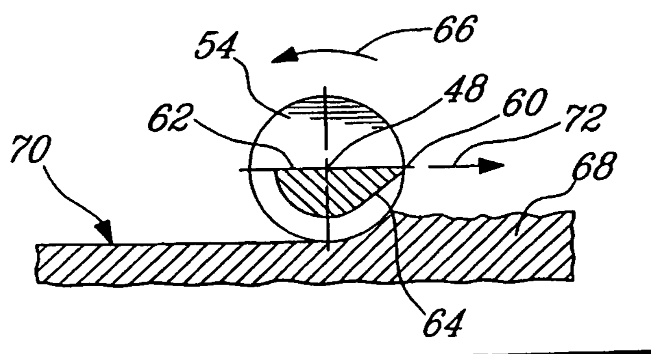
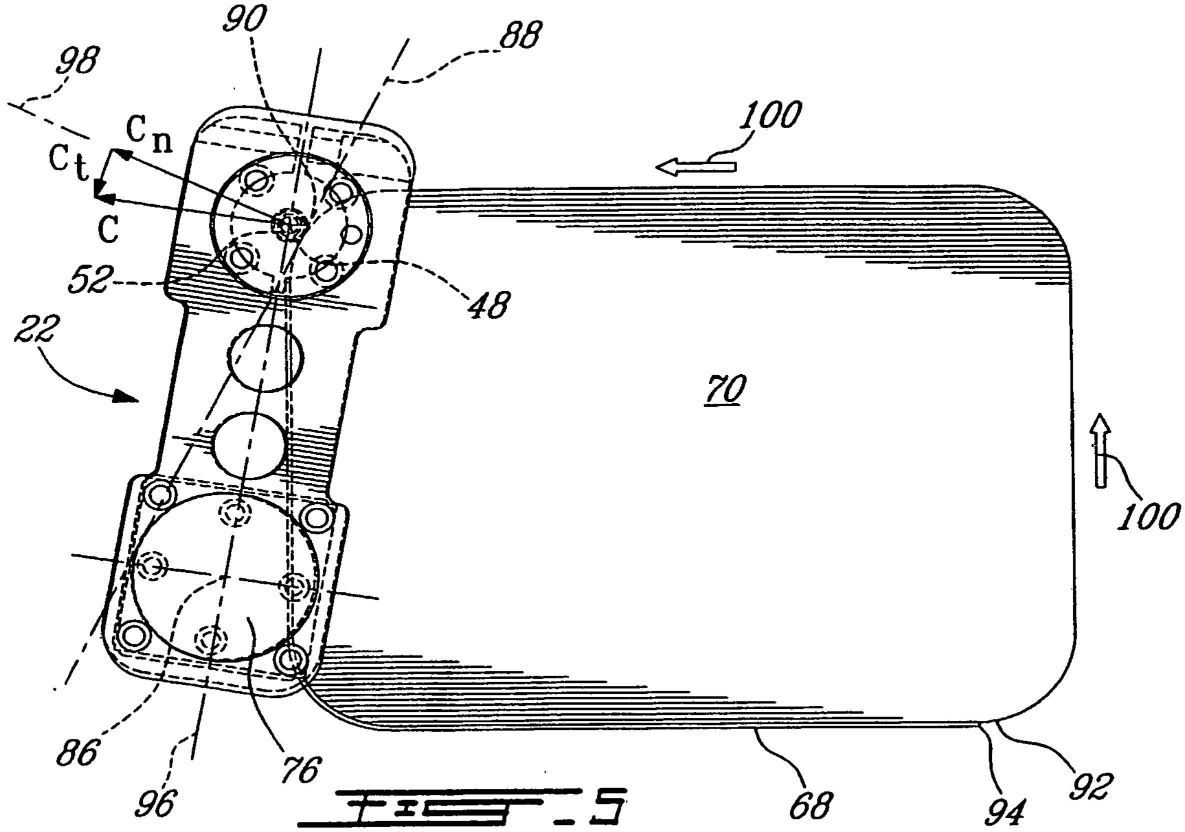


FIG. 4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C_t
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FIG. 5

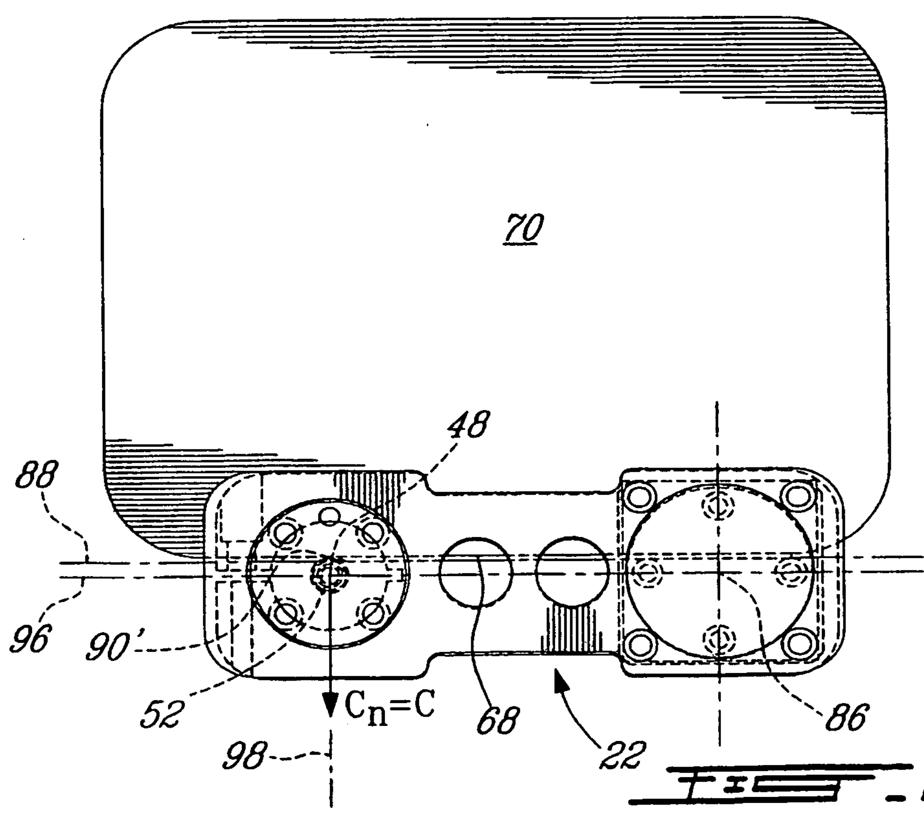
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FIG. 6

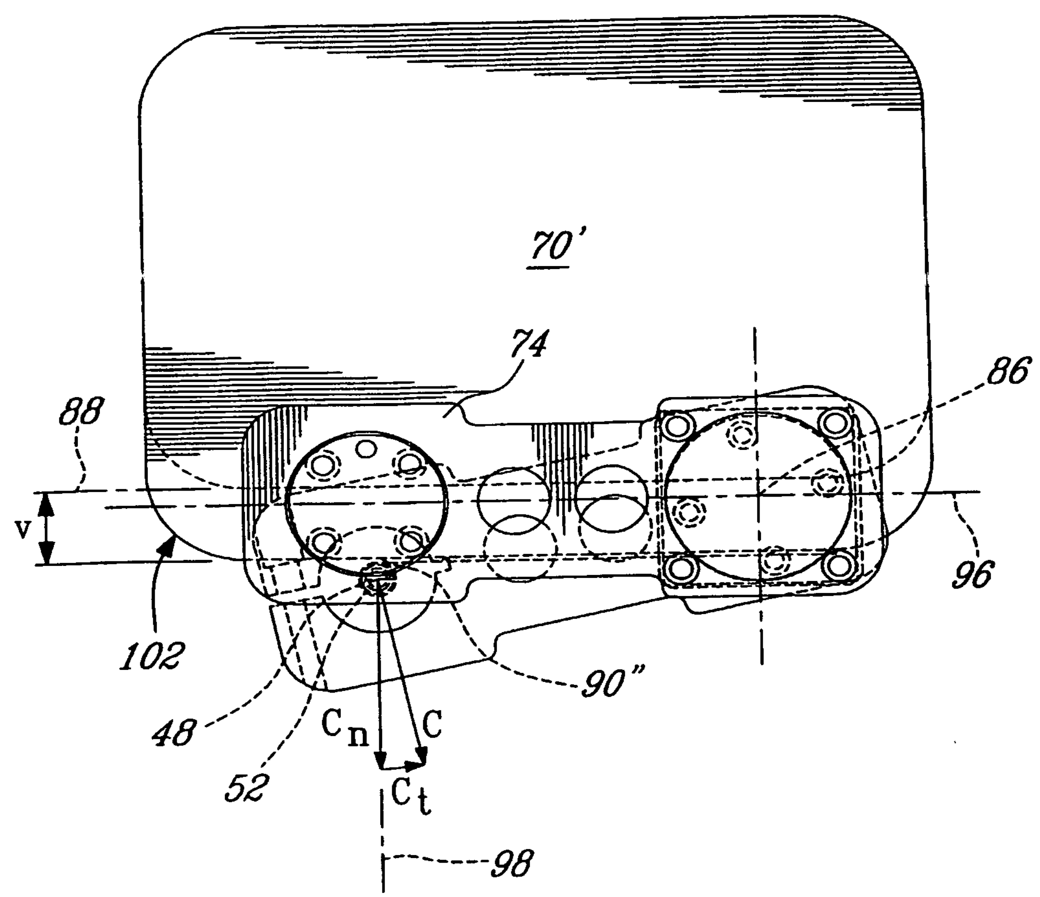

FIG. 7

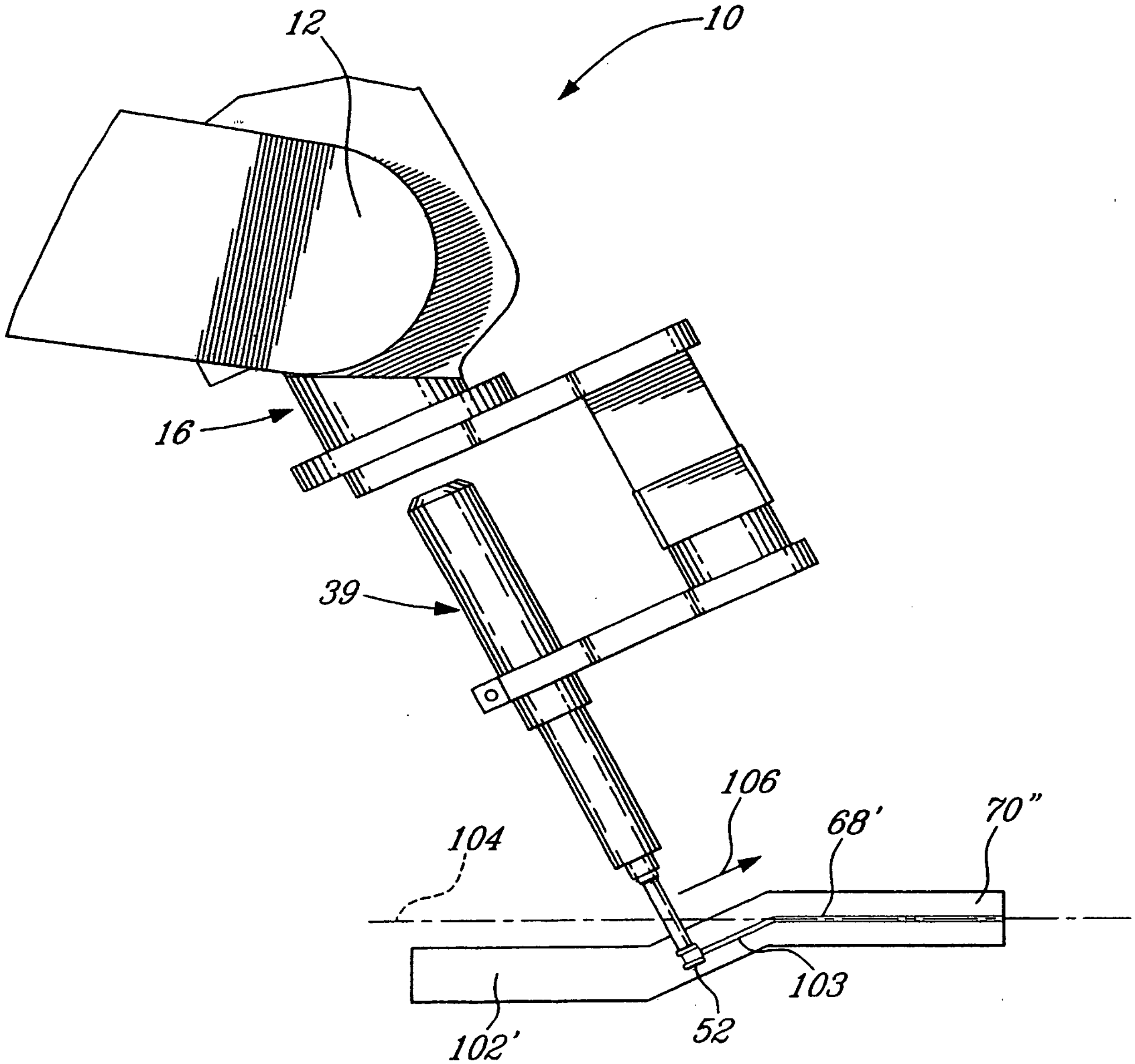

FIG. 8

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 02/00164

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 B25J17/02 B24B29/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 B25J B24B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 993 896 A (DOMBROWSKI DAVID M ET AL) 19 February 1991 (1991-02-19) cited in the application abstract	1-43
A	US 4 718 798 A (DUMARGUE GUY ET AL) 12 January 1988 (1988-01-12) cited in the application abstract; figure 1	1-43
A	EP 0 845 440 A (CENTRAL GLASS CO LTD) 3 June 1998 (1998-06-03) abstract; figure 1	1-43
A	DE 37 10 688 A (MANUTEC GMBH) 13 October 1988 (1988-10-13) column 2, line 43 -column 3, line 12; figure 1	1-43

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 June 2002	27/06/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Lasa, A

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	DE 37 38 619 A (DAIMLER BENZ AG) 1 June 1989 (1989-06-01) abstract; figure 1 -----	1-43

INTERNATIO L SEARCH REPORT

Information on patent family members

In[illegible] [illegible]pplication No

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